

Self-propulsion of flapping bodies in viscous fluids: Recent advances and perspectives

Shizhao Wang¹ · Guowei He¹ · Xing Zhang¹

Received: 14 January 2016 / Revised: 12 April 2016 / Accepted: 27 April 2016 / Published online: 11 August 2016

© The Chinese Society of Theoretical and Applied Mechanics; Institute of Mechanics, Chinese Academy of Sciences and Springer-Verlag Berlin Heidelberg 2016

Abstract Flapping-powered propulsion is used by many animals to locomote through air or water. Here we review recent experimental and numerical studies on self-propelled mechanical systems powered by a flapping motion. These studies improve our understanding of the mutual interaction between actively flapping bodies and surrounding fluids. The results obtained in these works provide not only new insights into biolocomotion but also useful information for the biomimetic design of artificial flyers and swimmers.

Keywords Flapping motion · Self-propulsion · Symmetry breaking · Passive flexibility · Flow-mediated interaction

1 Introduction

Flapping wings (or fins) serve as the propulsion system for many animals that locomote through air or water. These animals are able to achieve high efficiency and high maneuverability during locomotion. Flapping-powered flying and swimming have thus become a source of inspiration for the design of biomimetic aerial and underwater vehicles. Investigations into the physical principle that governs flapping-based propulsion are motivated by both intellectual curiosity and potential applications in civil and defense industries.

Studying flapping-wing propulsion as a scientific problem has a rather long history starting in the 1920s. Knoller [1] and Betz [2] were the first to observe that the thrust pro-

duced by a flapping wing has its roots in the lift force (Fig. 1). The first experimental verification of the Knoller–Betz effect was provided by Katzmayer [3]. During the following decade, flapping-wing propulsion attracted more attention. von Kármán and Burgers [4] offered a theoretical explanation that linked drag or thrust production with the location and orientation of wake vortices. Since then, several different methods have been used to investigate the flow field and thrust generation from flapping foils, for example, unsteady potential flow analysis [5–7], Navier–Stokes simulations [8–15], and experimental studies [16–22]. Owing to its connection with the biomimetic design of micro air vehicles (MAVs) and underwater automatic vehicles (UAVs), flapping-based propulsion has recently become one of the most active research areas of fluid dynamics.

Traditionally, in investigations of flapping-based propulsion, the flappers are either towed at known speed through a water tank or, equivalently, placed in a freestream at a given speed in a water tunnel. Sensors are then used to measure the thrust force produced by the flapping model. Under such conditions, the speed of towing (or oncoming flow) and the actuating kinematics are completely decoupled. This is dissimilar to the realistic scenarios in biolocomotion. An alternative approach is to allow the flapping foil to self-propel [23]. When a steady cruising speed is reached, the thrust force and the drag force experienced by the self-propelled body are balanced. There are many interesting and unreported fluid dynamical phenomena that occur when flapping bodies are allowed to move by self-propulsion, rather than held fixed in a freestream.

This review centers on studies of self-propelled flapping-powered systems interacting with viscous fluids. Works based on the traditional approach, i.e., actively or passively flapping bodies fixed in freestream, are not covered. Also, we

✉ Xing Zhang
zhangx@lnm.imech.ac.cn

¹ The State Key Laboratory of Nonlinear Mechanics (LNM),
Institute of Mechanics, Chinese Academy of Sciences,
Beijing 100190, China

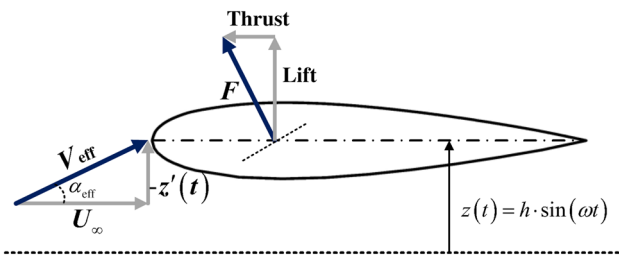


Fig. 1 Illustration of Knoller–Betz effect: generation of lift-based thrust in a flapping foil. U_∞ denotes the speed of the oncoming flow, z denotes the vertical position of the leading edge, and V_{eff} denotes the relative velocity vector between the oncoming flow and the flapping foil. For inviscid flow, the force F exerted on the foil is perpendicular to the direction of the relative velocity. The thrust can be considered as the force component projected onto the propulsion direction

focus on the situation in which self-propulsion occurs only in one degree of freedom and the flapping motion is actuated by very simple kinematics (plunging, pitching, or a combination of the two). Moreover, this paper aims at macroscopic locomotion in viscous fluids. Thus, works in the areas of Stokesian flow and inviscid flow are not included.

The rest of the paper is organized as follows. In Sect. 2, we review studies on self-propelled systems driven by plunging motion and on fore–aft symmetry. Section 3 focuses on how self-propulsion is affected by the presence of passive flexibility. Section 4 presents a discussion on the metrics for quantifying the propulsive efficiency of self-propulsion. Two types of flow-mediated interactions that involve self-propelled flapping bodies, namely, multibody interaction and interaction with a solid wall, are discussed in Sect. 5. The future outlook of this research area is addressed in Sect. 6.

2 Locomotion as a consequence of symmetry breaking

The simplest possible actuating kinematics of flapping-based propulsion is the plunging (heaving) motion. Vandenberghe et al. [24,25] proposed using a rotational geometry to study a self-propelled flapping-wing system driven by a plunging motion. In their apparatus, a flat rectangular wing was actuated at its center and forced to oscillate in the vertical direction. The wing was immersed in a water tank and allowed to rotate freely in the horizontal direction. As a symmetric system with respect to the vertical axis, any possible rotational motion of the wing can be attributed to the occurrence of clockwise–counterclockwise symmetry breaking.

One important finding in the experiments by Vandenberghe et al. [24,25] was the existence of a critical flapping Reynolds number below which no horizontal rotation occurred. When the flapping Reynolds number exceeded this critical value, the wing started to move and finally reached a terminal rotating speed. This finding may provide an explanation

of the change in locomotion strategy in some organisms with the variation in swimming speed. It was also found that near the onset of spontaneous rotation, the system exhibited complex hysteresis and bistability. Another important finding in these studies was that the Strouhal numbers fell within a reasonable range corresponding to efficient propulsion in aquatic animals. This finding suggested that this range of Strouhal number was naturally selected by self-propulsion. Thus, for aquatic animals, fine-tuning through feedback control is not necessary.

Motivated by the aforementioned experimental studies, some numerical simulations were conducted in a planar two-dimensional (2D) geometry. Alben and Shelley [26] showed that fore–aft symmetry breaking in self-propelled bodies could be related to the classical von Karman instability in symmetric wakes behind fixed bluff bodies. They also showed that body mass and slenderness play crucial roles in locomotion. Their numerical results also indicated that the hysteretic transitions from immobility to rotation observed in their experiments were the consequence of finite axle-bearing friction. Lu and Liao [27] predicted the dependency of the critical flapping Reynolds number on flapping frequency and amplitude. Zhang et al. [28] focused on the effect of chord-thickness ratio on dynamical behavior and wake structure. They identified three distinct types of motion in foils with an increasing chord-thickness ratio, i.e., low-amplitude oscillation, back-and-forth chaotic motion, and steady unidirectional locomotion. They also observed that an oblique vortex street could be produced in the wake behind very slender foils as a consequence of the breaking of up–down symmetry. Figure 2 shows the wake vortex structures around and behind the flapping foil for different states of motion. Deng and Caulfield [29] investigated the intrinsic connection between the instability observed in self-propelled flapping bodies with that observed in horizontally constrained flapping bodies. They found that the removal of the horizontal constraint could either suppress or encourage the development of instability in the flow, depending on the chord-thickness ratio. Recently, Hu and Xiao [30] performed simulations to study the effect of aspect ratio (AR) on the self-propulsion of three-dimensional wings. They found that the terminal speed achieved by the wings increased with increasing AR.

3 Influences of passive flexibility

Passive flexibility of wing/fins has long been recognized as an important factor in the aerodynamic (hydrodynamic) performance of insect flight and fish swimming. However, the scientific understanding of how propulsive performance is influenced by the flexibility of wings/fins is far from complete.

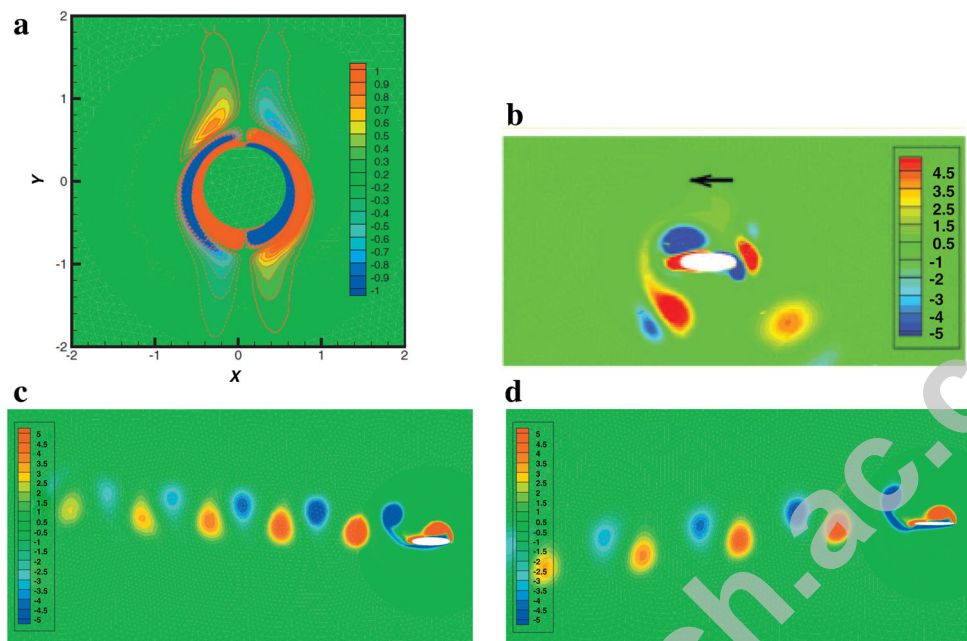


Fig. 2 (Color online) Wake vortex structures around and behind flapping foil for different states of motion. **a** Low-amplitude horizontal oscillation. **b** Back-and-forth chaotic motion. **c** Unidirectional locomotion (with a staggered reverse Karman vortex street). **d** Unidirectional locomotion (with a deflected reverse Karman vortex street). Figure taken from Zhang et al. [28]

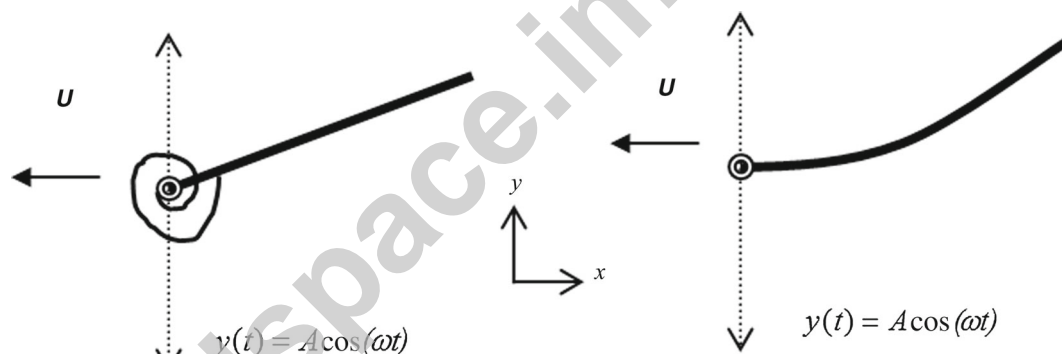


Fig. 3 Schematic diagrams of lumped-torsional-flexibility model (left) and solid continuum model (right) for a flexible self-propelled plunging foil

3.1 Lumped-torsional-flexibility model and solid continuum model

Spagnolie et al. [31] experimentally explored the effects of flexibility using the same experimental setup as that in [24, 25]. A torsion spring system was equipped to generate the passive pitching in heaving wings (Fig. 3). The researchers observed three regimes of dynamical behaviors, corresponding to different ranges in the driving frequency: one regime of outperformance (higher terminal velocity) with respect to the clamped wing, one regime of underperformance, and one hysteretic regime in which the wing can move either forward or backward. The terminal velocity in the flapping wing was found to peak when the driving frequency became closer to the system's resonance frequency. Some numer-

ical simulations in 2D geometry were also conducted in this study, and some experimental results were successfully reproduced. Zhang et al. [32] systematically investigated the lumped-torsional-flexibility system using 2D simulations and identified two different regimes in the flow state, i.e., periodic and nonperiodic. They also found that in the periodic regime, the direction of locomotion could be determined by the frequency ratio F (ratio of the natural frequency to the heaving frequency). Forward movement and backward movement were observed for $F > 1$ and $F \leq 1$, respectively. In the regime of forward locomotion, flexibility was found to enhance the propulsive performance. Using a 2D “ n -link” torsion spring model, Arora et al. [33] conducted similar numerical simulations to investigate the effect of F on the propulsive performance. Recently, Xiao et al. [34]

conducted three-dimensional (3D) simulations to investigate the effect of torsional flexibility on the self-propulsion of a plunging elliptic wing hinged about a spring. The focuses of this work were the influences of AR and the location of the pivot point.

An alternative route for studying the effects of chordwise flexibility on propulsion is to adopt a solid continuum model for the structure (Fig. 3). Experiments were conducted on a “merry-go-round” device (similar to that used in Refs. [24, 25]) by Thiria and Godoy-Diana [35] and Ramanarivo et al. [36] to study the effects of flexibility on the flying performance of flapping-wing flyers. A combined experimental and numerical study was carried out by Alben et al. [37] to investigate the self-propulsion of thin foils that were oscillated at the leading edge. To minimize friction, a sliding rail with an air-bearing system was used. They found resonance-like peaks in the swimming speed with variations in the foil’s length and rigidity. Using the potential flow model and an empirical formula to account for skin friction, they obtained good agreement between the model prediction and experimental results. It was also demonstrated that the experimental data on foil speed with respect to length and rigidity collapsed well onto the predicted scaling curves. A few numerical studies based on a solid continuum model of structure and viscous fluid model of flow can also be found in the recent literature. In the 2D studies by Lee and Lee [38], Hua et al. [39], and Zhu et al. [40] and the 3D study by Yeh and Alexeev [41, 42], it was demonstrated that moderate flexibility can improve the cruising velocity and efficiency of self-propelled plunging foils (or wings). Figure 4 shows the normalized cruising speed, swimming power, and propulsive efficiency as a function of dimensionless bending rigidity for several case studies in Ref. [40]. Three distinct regimes for the state of motion — forward, backward, and irregular — were identified by Hua et al. [39] and Zhu et al. [40]. Figure 5 shows the mode shapes, the phase plots of the free end (vertical velocity vs. vertical displacement), and the normalized power spectra of free-end vertical displacement corresponding to these three regimes. Furthermore, in these two studies, both a regular reverse Kármán vortex street and a deflected vortex street were observed. Zhu et al. [43] also investigated the effects of flexibility on the breaking of up–down symmetry in the wakes behind self-propelled plunging foils. It was found that adding flexibility could either suppress or encourage the occurrence of up–down symmetry breaking (which leads to the emergence of a deflected vortex street). Figure 6 shows the two opposite effects of flexibility on the symmetry properties of wakes.

3.2 Structural resonance, wake resonance, and performance optimization

One central question in studies concerning the effects of flexibility on flapping-based propulsion is the relationship

between performance optimization and structural resonance. There is some evidence that the peak cruising velocity (in self-propelled flappers) [31] or peak thrust (in tethered flappers) [44] can be achieved near the system’s resonant frequency. However, results from other studies [35, 36, 39, 40] indicate that the peak cruising velocity or peak propulsive efficiency were observed at a flapping frequency much lower than the resonant frequency. In a 3D numerical study by Yeh and Alexeev [42], it was found that the peak cruising velocity of a flexible plunging panel was reached at the resonance point, whereas the peak in efficiency was achieved at a nonresonance frequency. To summarize, the role of structural resonance in optimizing system performance is still controversial. What becomes clear is that the propulsive performance of a flexible flapping foil strongly depends on the structural resonance only when (1) the trailing-edge amplitude is maximized at the resonant frequency and (2) the effect of leading-edge separation on propulsion is negligible. Conversely, if (1) the trailing edge exhibits non-resonance-like behavior owing to a strong nonlinearity introduced by higher flapping amplitudes [36] or (2) large-scale separation near the leading-edge occurs [43], then optimized performance can be achieved at an off-resonance frequency.

The alternative rationale behind the performance optimization of a flapping-wing system is hydrodynamic wake resonance (rather than structural resonance). The hydrodynamic wake resonant frequency can be determined by performing linear stability analysis on the time-averaged wakes behind a flapping foil. The hydrodynamic wake resonant frequency is defined as the frequency for maximum spatial growth of instabilities in the averaged velocity profile. The peak efficiency is believed to occur when the flapping frequency coincides with the hydrodynamic wake resonant frequency. This argument has been validated in rigid flapping foils by Triantafyllou [45]. Recently, the validity of this principle was also demonstrated in flapping foils with active and passive flexibility [46–48]. It should be noted that validation analysis of the hydrodynamic wake resonance principles was conducted only in flappers fixed in a freestream. Whether this principle holds or not in self-propelled flappers remains an open question. Since time-averaged velocity profiles behind fixed and self-propelled flappers are different, the growth of instabilities also differs. Furthermore, for a self-propelled body, what is the suitable metric for measuring its propulsive efficiency is still debatable. A discussion regarding the metric for quantifying efficiency will be presented in Sect. 4.

3.3 Intrinsic link between passive and active flexibility

Besides flapping-based propulsion, undulatory propulsion is another commonly seen strategy in animal locomotion. Undulatory propulsion is mainly adopted by slender swimmers (such as eels), in which a traveling wave propagates

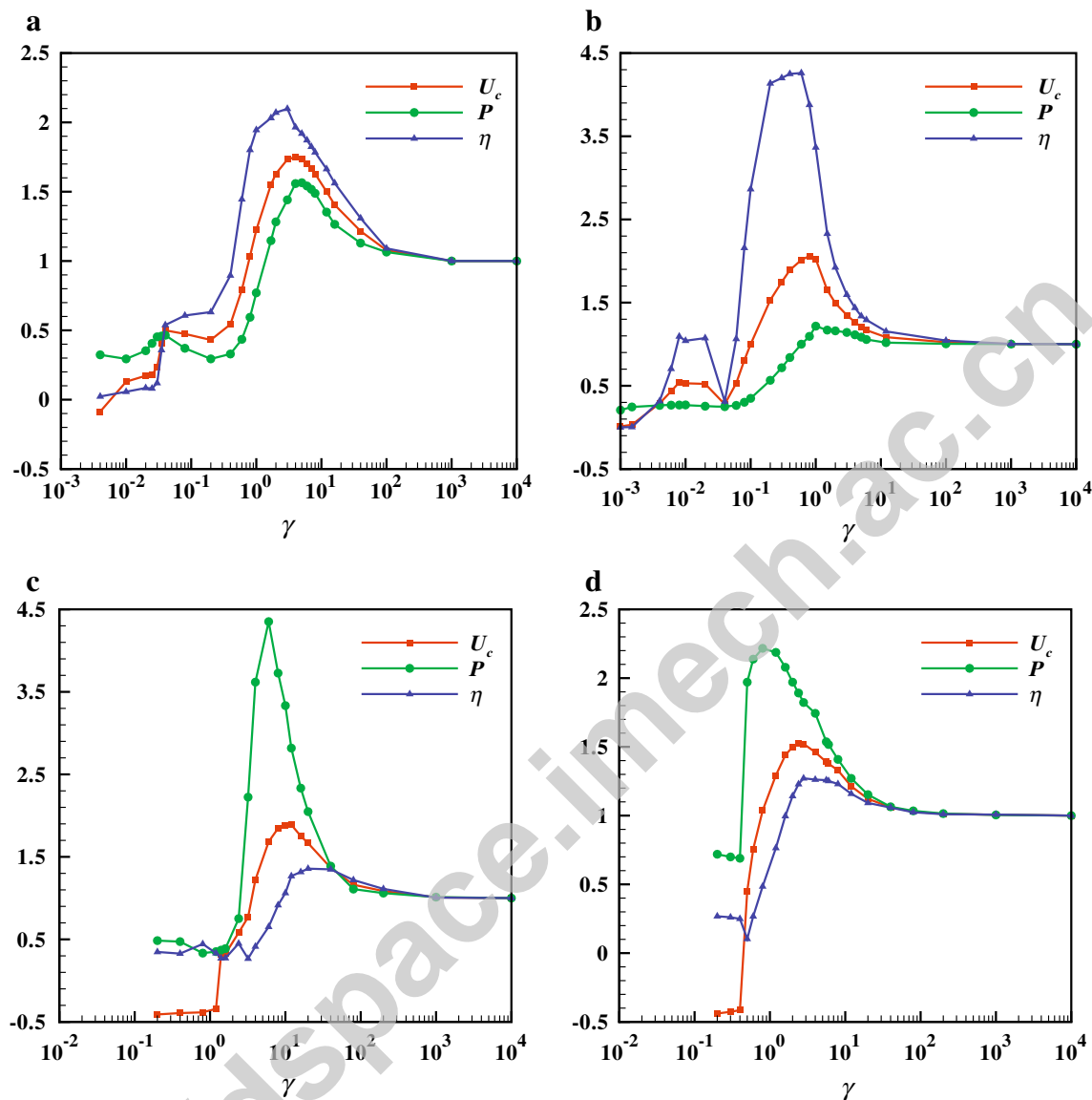


Fig. 4 Normalized cruising speed, swimming power, and propulsive efficiency as a function of dimensionless bending rigidity. The flapping Reynolds number is set to 200 for all cases. The dimensionless flapping amplitudes are 0.2 for cases **a** and **c** and 0.5 for cases **b** and **d**. The density ratios are 0.2 for cases **a** and **b** and 2.0 for cases **c** and **d**; solid lines with squares: cruising speed; solid lines with circles: swimming power; solid lines with triangles: propulsive efficiency all quantities were normalized using values obtained in a rigid foil. Figure taken from Zhu et al. [40]

along the deformable body. This anguilliform kinematics is driven by body muscular actions. The capability of producing body deformation in undulatory propulsion is also termed *active flexibility*. If only external biofluid dynamics is of concern, then there is no necessity to distinguish between active and passive flexibility. Actually, in some forms of biolocomotion, active flexibility and passive flexibility coexist and their contributions to body deformation cannot be easily unraveled.

In the biomimetic design of artificial swimmers, active flexibility is hard to mimic owing to the complex temporal and spatial coordination of many local actuations. Conversely, a design based on passive flexibility can be more

feasible. An intrinsic link between passive flexibility and active flexibility was recently discovered. Ramanarivo et al. [49] successfully reproduced the anguilliform kinematics by utilizing passive flexibility in artificial elastic swimmers. They presented some experiments on the self-propulsion of such swimmers on a free surface. In other work by Ramanarivo et al. [50], the researchers showed that strong damping that dissipates enough energy along a body can generate traveling-wave kinematics and prevent the buildup of stationary waves. The discovery of the passive elastic mechanism for mimicking muscular action in anguilliform swimming has opened the door to a new way of designing artificial swimmers.

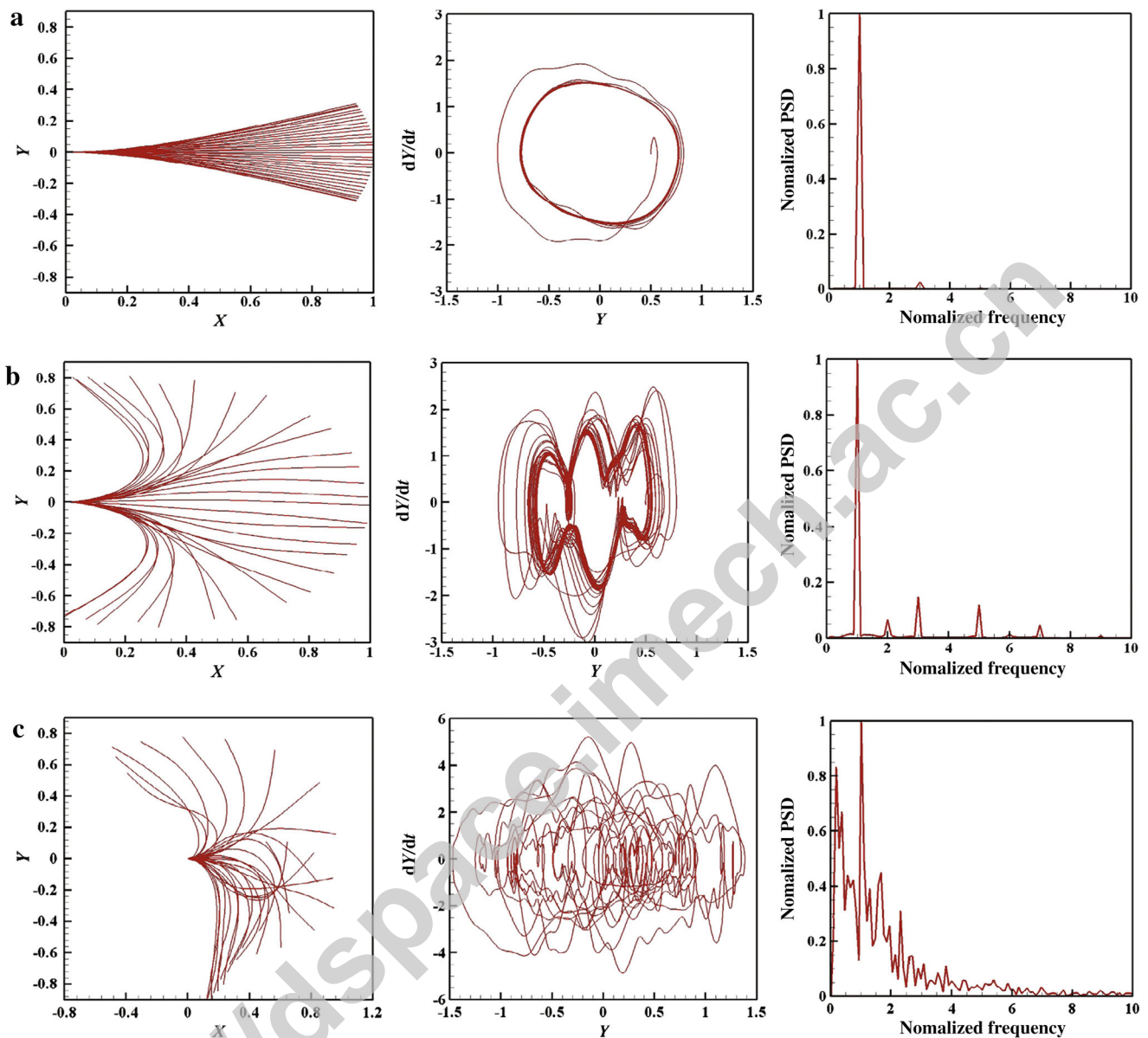


Fig. 5 Mode shape, phase plot of free end (vertical velocity vs. vertical displacement), and normalized power spectrum of free-end vertical displacement, corresponding to **a** forward motion, **b** backward motion, and **c** irregular motion. The flapping Reynolds number, dimensionless flapping amplitude, and density ratio are 200, 0.2, and 2.0, respectively. The dimensionless bending rigidities are 2.4, 0.4, and 0.12 for **a–c**, respectively. The positions of the flapping foil in the mode shape are plotted every $1/30$ of the forcing period and are in the frame moving with the leading edge. The displacement and velocity in the phase plot are in the laboratory frame. The frequency in the power spectrum was normalized by the flapping frequency. Figure taken from Zhu et al. [40]

4 Metrics for quantifying propulsive efficiency

The efficiency of propulsion can be defined as the ratio of useful power output to power input:

$$\eta = \frac{\bar{P}_{\text{out}}}{\bar{P}_{\text{in}}}. \quad (1)$$

For a tethered flapping-powered propulsor that produces a net thrust, the power output can be computed as

$$\bar{P}_{\text{out}} = \bar{T} \cdot \bar{U}, \quad (2)$$

where \bar{T} is the time-averaged net thrust, and \bar{U} is the average moving velocity.

However, for a self-propelled body under steady cruising conditions, the efficiency defined in Eq. (1) is always zero due to the force balance. Obviously, this efficiency of a self-propelled body is ill-defined. Two strategies can be used to overcome this obstacle. The first route is to separate *thrust* and *drag* through a *force decomposition* procedure. The sec-

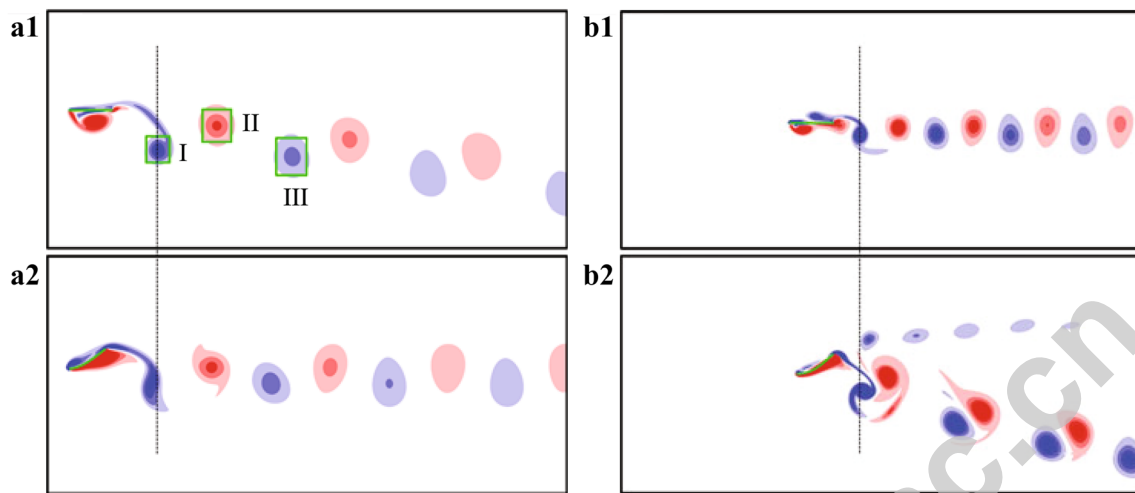


Fig. 6 (Color online) Vorticity contours for wakes of four cases **a1**, **a2**, **b1**, and **b2**. The flapping Reynolds number is set to 200 for all cases. The dimensionless flapping amplitude and density ratio are 1.0 and 0.2 for cases **a1** and **a2**. The dimensionless flapping amplitude and density ratio are 0.4 and 2.0 for cases **b1** and **b2**. The cruising velocity in case **a1** is the same as that in **a2**. The cruising velocity in case **b1** is the same as that in **b2**. The dimensionless bending rigidity is 10^4 for cases **a1** and **b1**. The dimensionless bending rigidities are 0.1 and 3.6 for cases **a2** and **b2**, respectively. Figure taken from Zhu et al. [43]

ond route is to measure efficiency using quantities that do not contain thrust.

Along the first route, the rational evaluation of efficiency relies on a meaningful procedure to obtain the thrust force. There is no unique way of defining thrust and drag in self-propelled swimmers. Borazjani and Sotiropoulos [51,52] computed the instantaneous (pressure and viscous) force components along the swimming direction. These force components then contributed to either drag or thrust, depending on their signs. Bale et al. [53] proposed using a dynamic decomposition based on the splitting of kinematics into drag- and thrust-producing mechanisms. Maertens et al. [54] replaced the thrust force by the towed resistance at cruising speed to evaluate the efficiency of free swimming. Thiria and Godoy-Diana [35] and Ramananarivo et al. [36] just used the thrust force produced by a tethered flapper to evaluate the efficiency of a self-propelled flapping foil. The separability of thrust and drag during free swimming is still debatable. Recently, the famous Gray's paradox was also found to be closely related to this unsolved question [55].

Schultz and Webb [56] did not believe that drag and thrust were separable in the case of self-propulsion and suggested a different route for quantifying efficiency. They proposed using a variable that denotes *miles per gallon* (length traveled per unit work input) as an efficiency metric

$$\eta_p = \frac{L_t}{W} = \frac{\bar{U}T}{\bar{P}_{in}T} = \frac{\bar{U}}{\bar{P}_{in}}. \quad (3)$$

Here L_t and W denote respectively the distance traveled and the work input within one flapping cycle, and T is the flapping period. This metric for efficiency is a dimensional quantity. To make rational comparisons among different swimmers,

it is necessary to normalize this quantity. There are several different ways to normalize it. For example, Kern and Koumoutsakos [57] used $\frac{1}{2}m\bar{U}f$, and the dimensionless quantity obtained is called the *propulsive efficiency*:

$$\tilde{\eta}_p = \frac{1}{2}m\bar{U}f \cdot \frac{\bar{U}}{\bar{P}_{in}} = \frac{\frac{1}{2}m\bar{U}^2}{\bar{P}_{in}T}. \quad (4)$$

Here m is the mass of the propulsor. This propulsive parameter has a clear physical meaning, which is the ratio of the kinetic energy eventually gained by the swimmer to the work done to the fluid within one flapping cycle. This metric was subsequently adopted in some studies to measure the efficiency in self-propelled bodies [32,40]. Alternatively, Liu et al. [58] chose mLf^2 , Yeh and Alexeev [42] chose $mLf^2/(2\beta)$, Eloy [59] chose $\rho V^{2/3}\bar{U}^2$, and Tokic and Yue [60] chose $mg\bar{U}$ to normalize it. Here f is the flapping frequency, L is the chord length, β is the ratio of the swimmer's density to the fluid density, ρ is the fluid density, V is the swimmer's volume, and g is the acceleration of gravity. The use of a normalized *cost of transport* (COT) to measure efficiency avoids the need to define *thrust* and *drag*. This is one favorable property of using such a metric for measuring efficiency. The unfavorable property of the normalized COT is that it may not be an efficiency-like quantity that ranges between zero and unity. To summarize, no consensus has been reached on which metric should be used to measure efficiency in self-propulsion. Caution is still needed when making comparisons among efficiencies obtained using different metrics.

5 Flow-mediated interactions

5.1 Multi-body interaction

The studies of flow interactions among multiple objects are partially motivated by self-organizing behaviors in animals, such as the formation of bird flocks and fish schools. In a study of fish schooling, the hydrodynamic advantage of a diamond-shaped array was addressed [61]. However, conflicting results have been obtained in the field and laboratory studies regarding the formation of fish schools. Thus, the function of hydrodynamics in fish schooling remains controversial.

Previously, the interactions of multiple bodies via fluid flow were studied in the context of placing these objects in a freestream [62–71]. This type of study has provided a basic understanding of flow-mediated interactions among stationary rigid bodies and actively (or passively) flapping bodies. However, such a setting is not suitable for investigating interactions in active systems such as fish schools. This is because in active systems, objects are moved by self-propulsion (interacting with the fluid). Thus, both the speeds of individuals and the interdistances among individuals are dynamically selected and cannot be prescribed.

Recently, some advances have been made in this research direction. By allowing objects to move freely (instead of fixing them in a freestream), researchers have discovered some interesting and previously unreported phenomena. Zhu et al. [72] designed a simple mathematical model consisting of two self-propelled flexible filaments. The two artificial “swimmers” are independently actuated at the leading edge by sinusoidal oscillations in the vertical direction and are not constrained in the horizontal direction. Two important findings from the simulations were reported: (1) stable aggregation of the pair can be formed spontaneously by locking the follower’s trajectory onto the vortex centers; (2) the follower can enjoy some energy benefits when the vortices generated by the leader are favorably arranged in the wake. Figure 7 shows the wake structures and the trajectory of the follower’s leading edge. It is seen that the follower always intercepts the vortex cores along a “realizable” trajectory. This is very different from the “slaloming” gait observed in a fish that maintained its position behind a stationary cylinder placed in freestream [73]. Unlike the passive system consisting of two flexible filaments [64], an “inverted drafting” (i.e., the leader can enjoy some energetic benefits) was never observed in this active system. Beck et al. [74] experimentally and numerically studied the interactions among an array of an “infinite” number of self-propelled flapping foils. In their experiments, a rotational geometry similar to that in Refs. [24,25] was used. In the simulations, a periodic boundary condition was used in the direction of swimming. It should be noted that in Ref. [74] the foils were constrained to move together at

the same velocity, and thus the interdistance was not allowed to vary. The major findings in Ref. [74] were as follows: (1) for a given actuating condition a fast mode and a slow mode exist in the cruising velocity and hysteretic transition behavior is exhibited; (2) swimmers enjoy energetic benefits in both modes except at the transitions between the two. The two aforementioned studies imply that hydrodynamic effects alone can result in stable aggregation and coherent collective locomotion. A similar viewpoint concerning the importance of fluid flows in self-organized living groups was also expressed in a recent work by De Rosier [75].

The work of Raspa et al. [76] also involved the self-propulsion of multiple bodies in fluids. They experimentally studied the self-propulsion of two rigid pitching foils placed side by side and separated by some distances. The two foils were independently actuated but forced to move forward together. By tuning the phase lag between the two foils’ pitching motions, two types of wake topology were produced. A zero phase lag resulted in a symmetric wake that resembled the kind observed behind a swimming jellyfish. A nonzero phase lag resulted in an asymmetric wake resembling that behind a swimming fish. The researchers compared the performance of these two types of actuating kinematics and concluded that flapping in a symmetric configuration may have locomotive advantages. This work yielded valuable information on the design and optimization of artificial biomimetic underwater vehicles.

5.2 Interaction with a solid wall

The flow-mediated interaction between a self-propelled flapping body and a solid wall can influence to a remarkable degree its propulsive performance. In some studies, this effect is also called the *unsteady ground* (or *wall*) *effect*. Such an effect can be found in fish swimming near a side wall [77] or substrate [78]. The physical mechanisms behind the unsteady ground effect are still not well understood. As a first step toward understanding the unsteady ground effect in swimming fish, the influences of wall confinement on the performance of mechanical models have been investigated.

Quinn et al. [79,80] conducted experiments on rigid foils undergoing plunging or pitching oscillations near a solid surface. They found that for tethered pitching foils, thrust was enhanced by the wall effect while the efficiency remained constant. For foils driven by a plunging motion and under self-propulsion, the flexible foils swam faster near the channel wall while maintaining the same propulsive efficiency. Under tethered conditions, the plunging foils were found to produce more thrust near the channel wall. The researchers argued that the thrust in the flapping foils was amplified by the wall effect primarily through enhanced circulation. In an experiment by Fernandez-Prats et al. [81], the propulsive dynamics of a self-propelled flexible foil actuated by

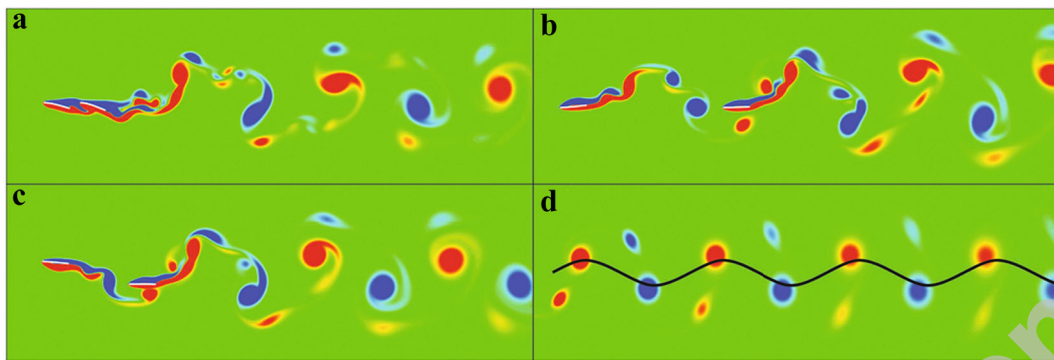


Fig. 7 (Color online) Wake structures of two self-propelled flapping filaments at different equilibrium separation distances. **a** $G = 0.2 L$ (G and L are the gap distance and body length, respectively). **b** $G = 5.0 L$. **c** $G = 0.2 L$. **d** Superimposition of follower's leading-edge trajectory corresponding to **b** on vortex street generated by one filament in isolated swimming. Red and blue: positive (counterclockwise) and negative (clockwise) vorticity, respectively. Figure taken from Zhu et al. [72]

a combined motion of plunging and pitching near a wall was investigated. It was observed that the wall effect could enhance cruising velocity by up to 25 %. They showed that the presence of a solid wall could reorient momentum in a manner favorable to the propulsion direction, and the enhanced cruising velocity was associated with the momentum reorientation. In an earlier experiment on a stingray-inspired flexible fin conducted by Blevins and Lauder [82], some contradictory observations were reported. The researchers found that the wall effect resulted in an increase in input power by up to 10 %, but no noticeable increase in the cruising speed was found.

The results obtained in these nonbiological models provide some insights into the unsteady wall effect in free-swimming aquatic animals. These results are also helpful in the design of biomimetic underwater vehicles capable of making use of such an effect.

6 Outlook

Recent experimental and numerical studies have improved our understanding of the interactions between self-propelled bodies and viscous fluids. The observations in these works have provided some insights into biolocomotion, and these results are helpful in biomimetic designs of artificial flyers and swimmers.

Although the problem setting is very simple, rich flow physics and complex behavior are exhibited in self-propelled flapping-foil systems with fore-aft symmetry. The critical conditions under which unidirectional locomotion emerges as a consequence of symmetry breaking are now clear. The similarities and differences between the wake symmetry property of such systems and that of horizontally constrained flapping systems merit further study.

Whether flexibility assists or impedes the self-propulsion of flapping bodies has attracted increasing attention in recent

years. Although some progress has been made, efforts are still needed to fully understand the relationship between structural resonance and performance optimization. To confirm whether the hydrodynamic resonance principle holds in self-propulsion, linear stability analysis should be conducted on the wakes behind self-propelled flappers. In addition, efforts are also needed to find a suitable metric for measuring efficiency in self-propulsion. The utilization of passive flexibility (fluid-structure interaction mechanism) to mimic active flexibility in anguilliform swimming is a relatively new research direction. More attentions should be paid to the parameter range for generating such kinematics. The combination of active and passive flexibility, or the use of controllable stiffness in propulsion, can be another research avenue.

In the study of flow-mediated interactions among multiple self-propelled bodies, some recent results suggested that the role of fluid flows in animal grouping should be reassessed. As to the energetic benefits of grouping, a detailed investigation should be conducted to examine how individuals manage to harvest energy from the vortical fluid environment during locomotion. Studies on more complex grouping configurations and actuating kinematics are also needed. In the study of unsteady wall effects in self-propelled bodies, whether the wall confinement enhances propulsive performance is still inconclusive. More experimental and numerical studies are required to clarify this issue.

The free swimming of a fish-like body [83] (or free flying of a bird-like body [84]) actuated by more complex kinematics is a natural extension of the research topic discussed here. The numerical simulation of such a problem is more demanding, in terms of high computational cost and (perhaps even) the need for advanced techniques (such as large-eddy simulation) to handle turbulence.

Acknowledgments The project was supported by the Chinese Academy of Sciences (Grants KJCX-SW-L08, KJCX3-SYW-S01) and the National Natural Science Foundation of China (Grants 11021262, 11023001, 11232011, 11372331).

References

- Knoller, R.: Die Gesetze des Luftwiderstandes. Flugund Motortchnik(Wien) **3**, 1–7 (1909) (in German)
- Betz, A.: Ein Beitrag zur Erklärung des Segelfluges. Z. für Flugtech. und Motorluftschiffahrt **3**, 269–272 (1912) (in German)
- Katzmayr, R.: Effect of Periodic Changes of Angle of Attack on Behavior of Airfoils. NACA TM-147 (1922)
- von Kármán, T., Burgers, J.M.: Aerodynamic Theory, vol. 2. Springer, Berlin (1934)
- Garrick, I.E.: Propulsion of a Flapping and Oscillating Airfoil. NACA 567 (1937)
- Tuncer, I.H., Platzer, M.F.: Thrust generation due to airfoil flapping. AIAA J. **34**, 324–331 (1996)
- Jones, K.D., Platzer, M.F.: Numerical computation of flapping-wing propulsion and power extraction. In: 35th Aerospace Sciences Meeting & Exhibit, Reno, NV (1997)
- Isogai, K., Shinmoto, Y., Watanabe, Y.: Effects of dynamic stall on propulsive efficiency and thrust of flapping airfoil. AIAA J. **37**, 1145–1151 (1999)
- Pederzani, J., Haj-Hariri, H.: Numerical analysis of heaving flexible airfoils in a viscous flow. AIAA J. **44**, 2773–2779 (2006)
- Ramamurti, R., Sandberg, W.: Simulation of flow about flapping airfoils using finite element incompressible flow solver. AIAA J. **39**, 253–260 (2001)
- Sarkar, S., Venkatraman, K.: Numerical simulation of incompressible viscous flow past a heaving airfoil. Int. J. Numer. Meth. Fluids **51**, 1–29 (2006)
- Sarkar, S., Venkatraman, K.: Numerical simulation of thrust generating flow past a pitching airfoil. Comput. Fluids **35**, 16–42 (2006)
- Tuncer, I.H., Platzer, M.F.: Computational study of flapping airfoil aerodynamics. AIAA J. Aircr. **37**, 514–520 (2000)
- Tuncer, I.H., Platzer, M.F.: Thrust generation due to airfoil flapping. AIAA J. **34**, 324–331 (1996)
- Young, J., Lai, J.C.S.: Oscillation frequency and amplitude effects on the wake of plunging airfoil. AIAA J. **42**, 2042–2052 (2004)
- Young, J., Lai, J.C.S.: Mechanisms influencing the efficiency of oscillating airfoil propulsion. AIAA J. **45**, 1695–1702 (2007)
- Anderson, J.M., Streitlien, K., Barrett, D.S., et al.: Oscillating foils of high propulsive efficiency. J. Fluid Mech. **360**, 41–72 (1998)
- Freymuth, P.: Propulsive vortical signature of plunging and pitching airfoils. AIAA J. **26**, 881–883 (1988)
- Heathcote, S., Gursul, I.: Flexible flapping airfoil propulsion at low reynolds number. AIAA J. **45**, 1066–1078 (2007)
- Jones, K.D., Dohring, C.M., Platzer, M.F.: Experimental and computational investigation of the Knoller–Betz Effect. AIAA J. **36**, 1240–1246 (1998)
- Koochesfahani, M.M.: Vortical patterns in the wake of an oscillating airfoil. AIAA J. **27**, 1200–1205 (1989)
- Read, D.A., Hoyer, F.S., Triantafyllou, M.S.: Forces on oscillating foils for propulsion and maneuvering. J. Fluids Struct. **17**, 163–183 (2003)
- Lauder, G.V., Anderson, E.J., Tangorra, J., et al.: Fish biorobotics: kinematics and hydrodynamics of self-propulsion. J. Exp. Biol. **210**, 2767–2780 (2007)
- Vandenbergh, N., Zhang, J., Childress, S.: Symmetry breaking leads to forward flapping flight. J. Fluid Mech. **506**, 147–155 (2004)
- Vandenbergh, N., Childress, S., Zhang, J.: On unidirectional flight of a free flapping wing. Phys. Fluids **18**, 99–124 (2006)
- Alben, S., Shelley, M.J.: Coherent locomotion as an attracting state for a free flapping body. Proc. Natl. Acad. Sci. USA **102**, 11163–11166 (2005)
- Lu, X.Y., Liao, Q.: Dynamic responses of a two-dimensional flapping foil motion. Phys. Fluids **18**, 4173–4180 (2006)
- Zhang, X., Ni, S.Z., Wang, S.Z., et al.: Effects of geometric shape on the hydrodynamics of a self-propelled flapping foil. Phys. Fluids **21**, 593–598 (2009)
- Deng, J., Caulfield, C.P.: Dependence on aspect ratio of symmetry breaking for oscillating foils: implications for flapping flight. J. Fluid Mech. **787**, 16–49 (2015)
- Hu, J., Xiao, Q.: Three-dimensional effects on the translational locomotion of a passive heaving wing. J. Fluids Struct. **46**, 77–88 (2014)
- Spagnolie, S.E., Moret, L., Shelley, M.J., et al.: Surprising behaviors in flapping locomotion with passive pitching. Phys. Fluids **22**, 041903 (2009)
- Zhang, J., Liu, N.S., Lu, X.Y.: Locomotion of a passively flapping flat plate. J. Fluid Mech. **659**, 43–68 (2010)
- Arora, N., Gupta, A., Hikaru, A., et al.: Propulsion of a plunging flexible airfoil using a torsion spring model. In: AIAA Aviation, 33rd AIAA Applied Aerodynamics Conference, Dallas (2015)
- Xiao, Q., Hu, J., Liu, H.: Effect of torsional stiffness and inertia on the dynamics of low aspect ratio flapping wings. Bioinspir. Biomim. **9**, 016008 (2014)
- Thiria, B., Godoy-Diana, R.: How wing compliance drives the efficiency of self-propelled flapping flyers. Phys. Rev. E **82**, 015303 (2010)
- Ramanarivo, S., Godoy-Diana, R., Thiria, B.: Rather than resonance, flapping wing flyers may play on aerodynamics to improve performance. Proc. Natl. Acad. Sci. USA **108**, 5964–5969 (2011)
- Alben, S., Charles, W., Baker, T.V., et al.: Dynamics of freely swimming flexible foils. Phys. Fluids **24**, 051901 (2012)
- Lee, J., Lee, S.: Fluid-structure interaction for the propulsive velocity of a flapping flexible plate at low reynolds number. Comput. Fluids **71**, 348–374 (2013)
- Hua, R.N., Zhu, L.D., Lu, X.Y.: Locomotion of a flapping flexible plate. Phys. Fluids **25**, 121901 (2013)
- Zhu, X.J., He, G.W., Zhang, X.: Numerical study on hydrodynamic effect of flexibility in a self-propelled plunging foil. Comput. Fluids **97**, 1–20 (2014)
- Yeh, P.D., Alexeev, A.: Free swimming of an elastic plate plunging at low Reynolds number. Phys. Fluids **26**, 053604 (2014)
- Yeh, P.D., Alexeev, A.: Effect of aspect ratio in free-swimming plunging flexible plates. Comput. Fluids **124**, 220–225 (2015)
- Zhu, X.J., He, G.W., Zhang, X.: How flexibility affects the wake symmetry properties of a self-propelled plunging foil. J. Fluid Mech. **751**, 164–183 (2014)
- Michelin, S., Smith, S.G.L.: Resonance and propulsion performance of a heaving flexible wing. Phys. Fluids **21**, 071902 (2009)
- Triantafyllou, G.S.: Optimal thrust development in oscillating foils with application to fish propulsion. J. Fluids Struct. **7**, 205–224 (1993)
- Moored, K.W., Dewey, P.A., Smits, A.J., et al.: Hydrodynamic wake resonance as an underlying principle of efficient unsteady propulsion. J. Fluid Mech. **708**, 329–348 (2012)
- Moored, K.W., Dewey, P.A., Boschitsch, B.M., et al.: Linear instability mechanisms leading to optimally efficient locomotion with flexible propulsors. Phys. Fluids **26**, 041905 (2014)
- Zhu, X.J., He, G.W., Zhang, X.: Underlying principle of efficient propulsion in flexible plunging foils. Acta Mech. Sin. **30**, 839–845 (2015)
- Ramanarivo, S., Godoy-Diana, R., Thiria, B.: Passive elastic mechanism to mimic fish-muscle action in anguilliform swimming. J. R. Soc. Interface **10**, 20130667 (2013)
- Ramanarivo, S., Godoy-Diana, R., Thiria, B.: Propagating waves in bounded elastic media: transition from standing waves to anguilliform kinematics. Europhys. Lett. **105**, 54003 (2014)
- Borazjani, I., Sotiropoulos, F.: Numerical investigation of the hydrodynamics of carangiform swimming in the transitional and inertial flow regimes. J. Exp. Biol. **211**, 1541–1558 (2008)

52. Borazjani, I., Sotiropoulos, F.: Numerical investigation of the hydrodynamics of anguilliform swimming in the transitional and inertial flow regimes. *J. Exp. Biol.* **212**, 576–592 (2009)
53. Bale, R., Shirgaonkar, A.A., Neveln, I.D., et al.: Separability of drag and thrust in undulatory animals and machines. *Sci. Rep.* **4**, 7329 (2014)
54. Maertens, A.P., Triantafyllou, M.S., Yue, D.K.: Efficiency of fish propulsion. *Bioinspir. Biomim.* **10**, 046013 (2015)
55. Bale, R., Hao, M., Bhalla, A.P., et al.: Gray's paradox: a fluid mechanical perspective. *Sci. Rep.* **4**, 5904 (2014)
56. Schultz, W.W., Webb, P.W.: Power requirements of swimming: do new methods resolve old questions? *Integr. Comp. Biol.* **42**, 1018–1025 (2002)
57. Kern, S., Koumoutsakos, P.: Simulations of optimized anguilliform swimming. *J. Exp. Biol.* **209**, 4841–4857 (2006)
58. Liu, G., Yu, Y.L., Tong, B.G.: Optimal energy-utilization ratio for long-distance cruising of a model fish. *Phys. Rev. E* **86**, 016308 (2012)
59. Eloy, C.: On the best design for undulatory swimming. *J. Fluid Mech.* **717**, 48–89 (2013)
60. Tokic, G., Yue, D.K.: Optimal shape and motion of undulatory swimming organisms. *Proc. R. Soc. B* **279**, 3065–3074 (2012)
61. Weihs, D.: Hydromechanics of fish schooling. *Nature* **241**, 290–291 (1973)
62. Zdravkovich, M.M.: Review of flow interference between two circular cylinders in various arrangements. *J. Fluids Eng.* **99**, 618–633 (1977)
63. Ristroph, L., Zhang, J.: Anomalous hydrodynamic drafting of interacting flapping flags. *Phys. Rev. Letts.* **101**, 6797–6800 (2008)
64. Alben, S.: Wake-mediated synchronization and drafting in coupled flags. *J. Fluid Mech.* **641**, 489–496 (2009)
65. Zhu, L.D.: Interaction of two tandem deformable bodies in a viscous incompressible flow. *J. Fluid Mech.* **635**, 455–475 (2009)
66. Kim, S., Huang, W.X., Sung, H.J.: Constructive and destructive interaction modes between two tandem flexible flags in viscous flow. *J. Fluid Mech.* **661**, 511–521 (2010)
67. Uddin, E., Huang, W.X., Sung, H.J.: Interaction modes of multiple flexible flags in a uniform flow. *J. Fluid Mech.* **729**, 563–583 (2013)
68. Wang, Z., Russell, D.: Effect of forewing and hindwing interactions on aerodynamic forces and power in hovering dragonfly flight. *Phys. Rev. Letts.* **99**, 12243–12254 (2007)
69. Deng, J., Shao, X.M., Yu, Z.S.: Hydrodynamic studies on two traveling wavy foils in tandem arrangement. *Phys. Fluids* **19**, 113104 (2007)
70. Uddin, E., Huang, W.X., Sung, H.J.: Actively flapping tandem flexible flags in a viscous flow. *J. Fluid Mech.* **780**, 120–142 (2015)
71. Tian, F.B., Wang, W.Q., Wu, J., et al.: Swimming performance and vorticity structures of a mother-calf pair of fish. *Comput. Fluids* **124**, 1–11 (2016)
72. Zhu, X.J., He, G.W., Zhang, X.: Flow-mediated interactions between two self-propelled flapping filaments in tandem configuration. *Phys. Rev. Letts.* **113**, 238105 (2014)
73. Liao, J.C., Beal, D.N., Lauder, G.V., et al.: Fish exploiting vortices decrease muscle activity. *Science* **302**, 1566–1569 (2003)
74. Becker, A.D., Masoud, H., Newbolt, J.W., et al.: Hydrodynamic schooling of flapping swimmers. *Nat. Commun.* **6**, 8514 (2015)
75. De Rosier, A.: Fluid forces enhance the performance of an aspirant leader in self-organized living groups. *PLoS One* **9**, e114687 (2014)
76. Raspa, V., Godoy-Diana, R., Thiria, B.: Topology-induced effect in biomimetic propulsive wakes. *J. Fluid Mech.* **729**, 377–387 (2013)
77. Webb, P.W.: The effect of solid and porous channel walls on steady swimming of steelhead trout *Oncorhynchus mykiss*. *J. Exp. Biol.* **178**, 97–108 (1993)
78. Webb, P.W.: Kinematics of plaice, *Pleuronectes platessa*, and cod, *Gadus morhua*, swimming near the bottom. *J. Exp. Biol.* **205**, 2125–2134 (2002)
79. Quinn, D.B., Moored, K.W., Dewey, P.A., et al.: Unsteady propulsion near a solid boundary. *J. Fluid Mech.* **742**, 152–170 (2014)
80. Quinn, D.B., Lauder, G.V., Smits, A.J.: Flexible propulsors in ground effect. *Bioinspir. Biomim.* **9**, 036008 (2014)
81. Fernandez-Prats, R., Raspa, V., Thiria, B., et al.: Large-amplitude undulatory swimming near a wall. *Bioinspir. Biomim.* **10**, 016003 (2015)
82. Blevins, E.L., Lauder, G.V.: Swimming near the substrate: a simple robotic model of stingray locomotion. *Bioinspir. Biomim.* **8**, 016005 (2013)
83. Bottom II, R.G., Borazjani, I., Blevins, E.L., et al.: Hydrodynamics of swimming in stingrays: numerical simulations and the role of the leading-edge vortex. *J. Fluid Mech.* **788**, 407–443 (2016)
84. Zhu, L.L., Guan, H., Wu, C.J.: A study of a three-dimensional self-propelled flying bird with flapping wings. *Sci. China Ser. G* **58**, 1–16 (2015)